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The objective was to observe, describe, and understand the mechanisms underlying North Pacific Ocean variability that affect North American weather and climate. Within the scope of the project's ultimate long-term goals, the specific objective of the partnership developed under NOPP funding was to extend in-situ TAO array observations North of 20 N, and in-situ acoustic measurements of integrated heat content (ATOC) to the southern and western parts of the North Pacific Ocean, and to combine these measurements with altimetric data in eddy-resolving ocean circulation models to produce optimal nowcasts and forecasts. Particular emphasis was placed on understanding the impact of the so-called Pacific Decadal Oscillation (PDO).

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Monitoring the North Pacific for Improved Ocean, Weather and Climate Forecasts

Final Report

National Ocean Partnership Program

July, 2002

Partnering Institutions and Agencies

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National Environmental Satellite, Data and Information Service (NESDIS)
(Robert E. Cheney, P.I.)
Pacific Marine Environmental Laboratory (PMEL)
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U.S. Navy
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Scripps Institution of Oceanography (SIO)
(Peter F. Worcester, P.I.)

Goal

The goal of this project was to bring together a unique set of observational and modeling opportunities that existed within the partnering institutions and agencies to monitor the North Pacific Ocean with the ultimate purpose of improving weather and climate forecasts over the North American continent.

Objective

The objective was to observe, describe, and understand the mechanisms underlying North Pacific Ocean variability that affect North American weather and climate. Within the scope of the project's ultimate long-term goals, the specific objective of the partnership developed under NOPP funding was to extend in-situ TAO array observations North of 20 N, and in-situ acoustic measurements of integrated heat content (ATOC) to the southern and western parts of the North Pacific Ocean, and to combine these measurements with altimetric data in eddy-resolving ocean circulation models to produce optimal nowcasts and forecasts. Particular emphasis was placed on understanding the impact of the so-called Pacific Decadal Oscillation (PDO).

1) North Pacific Moorings

a) Moorings

Under the auspices of this program the Pacific Marine Environmental Laboratory (PMEL), developed a more robust version of its standard ATLAS mooring used in the Tropical Atmosphere Ocean (TAO) array. This high-latitude ATLAS was designed to withstand the harsh ocean environment of the North Pacific for periods up to one year. Moorings were equipped with a complete set of sensors for air-sea flux computations, plus ocean temperature, salinity, and velocity measurements. Two deployments were made at Ocean Station PAPA (50N, 145W) and one deployment at 35N, 165W. Data were transmitted in real-time every three hours directly to a receiving antenna at PMEL via GOES satellite.

After a first deployment at PAPA was foreshortened by loss of the instrumented tower on the buoy, the program was successful in collecting year long records at both locations in 1999-2000.

Data are freely accessible on the web at:
http://www.pmel.noaa.gov/toga-tao/nopp/deliv/

Analysis of the buoy data is underway at PMEL and elsewhere. Since termination of the NOPP program, design elements of the high latitude ATLAS have been incorporated into the tropical ATLAS system for enhanced measurements of surface fluxes, ocean

salinities, and velocities. Additionally, elements of the high latitude buoy hull and mooring design have been used in an array for the Deep-ocean Assessment and Reporting of Tsunamis (DART). (see http://www.pmel.noaa.gov/tsunami/Dart/).

b) Acoustic Receivers for Moorings

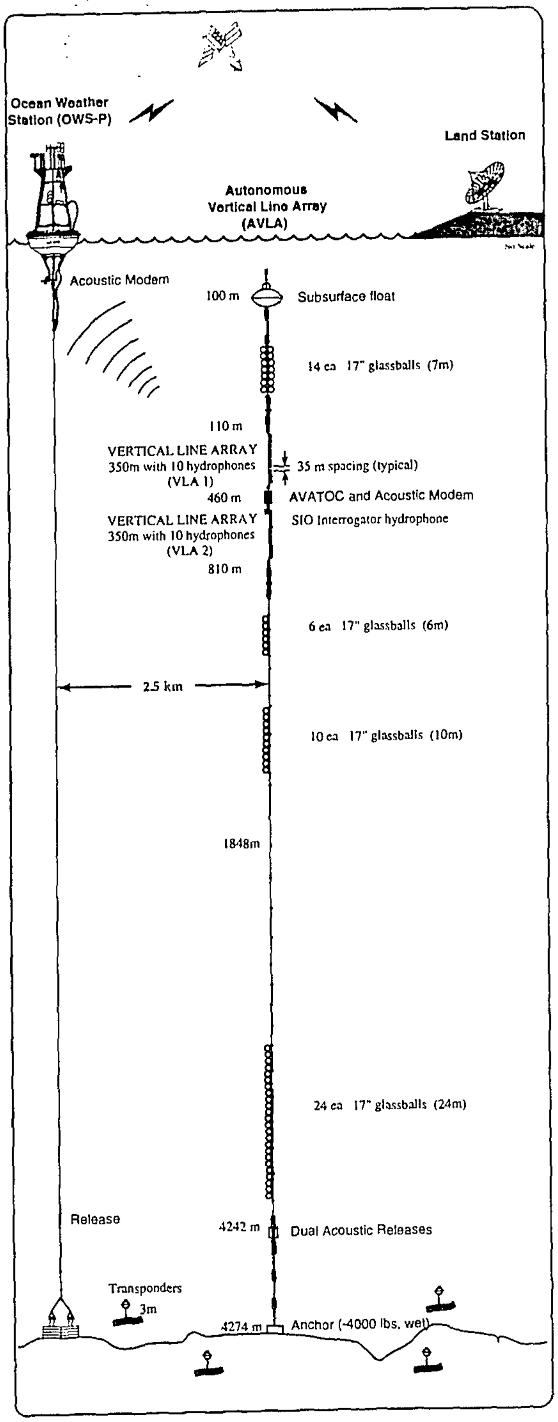
i) Mooring Design

A further objective of the project was to develop and deploy acoustic receivers to be used in conjunction with these moorings. The moorings were designed with satellite telemetry systems to provide near real-time data. Scripps was responsible for development and deployment of an acoustic receiver for use in conjunction with the surface moorings, to receive the signals transmitted by acoustic sources installed north of Kauai and off central California by the Acoustic Thermometry of Ocean Climate (ATOC) project for subsequent satellite transmission to shore. The goal was to develop a new, easy to use, and low cost acoustic receiver that could be used to supplement the ATOC array. The ultimate goal was to provide measurements of spatially-averaged ocean temperature and heat content *between* the moorings and one or more acoustic sources, to complement the point measurements made *at* the moorings.

The original plan was to attach the acoustic receiver directly to the surface mooring line. Detailed engineering analyses indicated that the development of an acoustic receiver that could survive, provide high quality acoustic data, and not endanger the structural integrity of the mooring when connected directly to a surface mooring moving in response to wave and wind action in a harsh ocean environment would be highly problematical. We therefore chose to use a two-mooring system at OWS PAPA. In this approach the acoustic receiving equipment is installed on a subsurface mooring located adjacent to the surface mooring, with an acoustic telemetry link to transfer data from the subsurface mooring to the surface mooring, for subsequent satellite telemetry to shore. Our conclusion was that the appropriate engineering solution is a function of location. In regions with harsh surface conditions, such as the Gulf of Alaska, it will likely be necessary to use two-mooring systems to obtain acoustic data of adequate quality. In regions with more benign wind and wave conditions, such as the tropics, it will probably prove feasible to include an integral acoustic receiver on the surface mooring, resulting in a significantly simpler overall system.

Thus, we proceeded in parallel on two fronts:

(i) We developed a two-mooring system for installation at OWS PAPA, with particular emphasis on development and testing of the acoustic telemetry system needed to obtain real-time data.



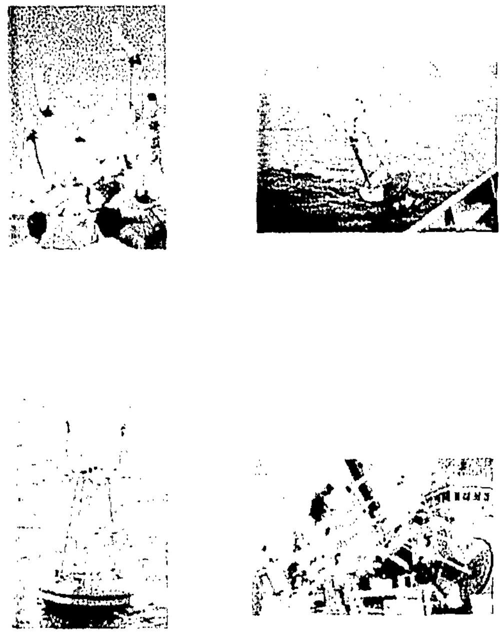


Figure 1. Ocean Weather Station Papa Moorings. Left, schematic, right, deployment.

(ii) We began development of a Simple Tomographic Acoustic Receiver (STAR) data acquisition system for use in more benign environments and as a stand-alone autonomous system.

OWS PAPA. An engineering test mooring designed to withstand the harsh environment of the North Pacific was deployed at OWS PAPA in September 1998 and was recovered in June 1999. A subsurface mooring (no surface expression) instrumented with a Vertical Line Array (VLA) receiver was installed 2.5 km away. Unfortunately, shortly after the moorings were deployed the GOES transmitter dedicated to the acoustic data failed. However, in the short time it was operational, acoustic data received from an ATOC source off Kauai were successfully received and processed, acoustically telemetered to the surface mooring, and sent by GOES satellite to shore. We were therefore able to demonstrate the basic concept, although we were not able to obtain acoustic data in real-time throughout the deployment. The acoustic receiver also recorded all data internally, for analysis following recovery.

The acoustic data obtained from the receiver installed at OWS PAPA have been processed and time series of acoustic travel times generated. Initial efforts to compare the acoustic travel time data with ocean general circulation model outputs were started with NOPP funding. The analysis effort has now been transitioned to the NPAL project. The travel time data from OWS PAPA are being combined with the other ATOC/NPAL data and compared with model outputs.

ii) New Acoustic Receiver Design

A new, easy to use, and low-cost acoustic receiver was designed, intended for use in acoustic remote sensing methods, and long-term monitoring the North Pacific (and other ocean basins). The receivers are intended to supplement existing Navy facilities which are limited in spatial coverage.

A key effort in developing the new system has been extensive testing of a new, low-power, microprocessor-controlled crystal oscillator (MCXO), and a smaller, and lower-cost Rb atomic frequency standard to replace the units currently in use. The availability of these two new oscillators, both of which were under development during the last few years and only very recently have actually gone into production, is fundamental to our ability to develop a low-cost and easy to use receiver.

The overall design of the receiver has been completed. Construction of five receivers is well underway at the time of this writing and is expected to be completed with funding provided by ONR's North Pacific Acoustic Laboratory (NPAL) project.

2) Altimetric Data

NOAA-NESDIS' Laboratory for Satellite Altimetry is now generating and supplying ERS-2 altimeter data sets in near real-time to the Navy (NRL-SSC) for assimilation in their eddy-resolving Pacific model. This data is also incorporated into NAVOCEANO's Altimeter Data Fusion Center, and is included in the assimilation scheme of the global layered ocean model running at Fleet Numerical and Meteorology and Oceanography Center (FNMOC).

The NOPP funds have enabled a continuing collaboration with the Delft University of Technology who compute the ERS-2 orbits. We also made significant improvements in both the accuracy and timeliness of the ERS-2 data.

Additionally, personnel funded by this proposal worked with the Navy to get data from the Geosat Follow-On altimeter into the operational data stream. Despite a host of problems with the satellite during the first 2 years of the mission, the data have been reliable since the end of 1999.

Relevant documentation can be found at:

<u>Operational and Precise Orbit Determination for Geosat Follow-On Altimetry</u>, *Fall 2001 AGU Meeting: EOS Trans. AGU*, **82(47) Suppl.**, Dec. 10, 2001.

<u>ERS-2 Altimetry in Operational NOAA Forecast Models</u>, *Proc. 4th ERS Symp., Gothenberg, Sweden*, October 2000.

<u>Calibration/Validation results for Geosat Follow-On</u>, *Spring 2000 AGU Meeting: EOS Trans. AGU*, **81(19) Suppl.**, June 2, 2000.

<u>Real-Time ERS Altimetry at NOAA</u>, *Earth System Monitor*, Vol.9 #2, March 1999.

3) Layered Ocean Model

The NOPP project played an important role in the development of an ocean prediction system which is now operational. The model was first run as a Pacific system, but has now been expanded to global system. The real-time ERS-2 altimeter data stream was started as part of this NOPP project and is now part of the routine data stream used by the operational ocean prediction system and other ocean products.

The basic product is a real-time nowcast/forecast from the 1/16° global Naval Research Lab (NRL) Layered Ocean Model (NLOM), including snapshots, animations and forecast verification statistics for many zoom regions, mainly sea surface height (SSH), sea surface temperature (SST) and surface currents. Direct model-data comparisons are also made.

The 1/16° global NLOM is an operational product run daily by the Naval Oceanographic Office (NAVOCEANO) with atmospheric forcing from the Navy Operational Global Atmospheric Prediction System (NOGAPS) and assimilation of SST and satellite altimeter data obtained via the NAVOCEANO Altimeter Data Fusion Center.

An example of ERS-2 data and its incorporation into the 1/4 degree global NRL Layered Ocean Model is shown in Fig. 2.

Results that can be seen at:

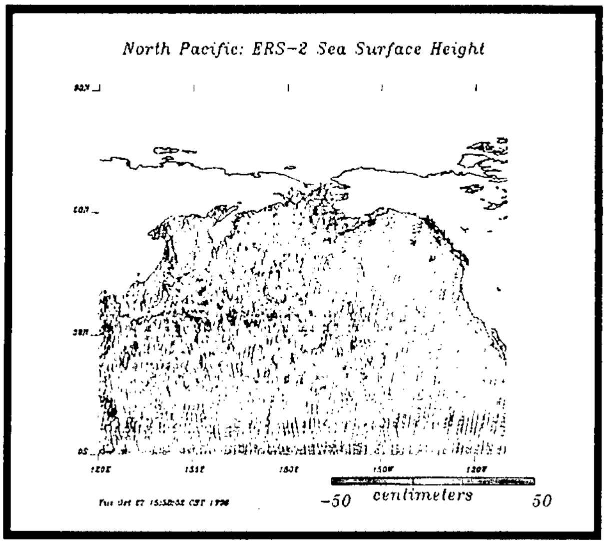
http://www7320.nrlssc.navy.mil/global_nlom

4) Pacific Decadel Oscillation

We have studied the PDO using historical NCEP/NCAR data to assess the impact of SST anomalies on the atmosphere over the North Pacific, and have concluded that the effect is significant and important. Previous studies using monthly mean data, and some GCM studies, suggest that the atmosphere largely just forces the ocean, and is relatively insensitive to SST anomalies. Two atmospheric basic states for the central North Pacific have been considered to analyze the hypothesis that the atmosphere does respond significantly to sea surface anomalies, viz., persistent ridges of high pressure (blocks) and persistent conditions of enhanced zonal flow. These structures tend to persist for roughly 10-30 days and have a profound effect on the weather downstream over North America. Further, these persistent anomalies, and the high-frequency transients with which they interact, exhibit significant differences between different phases of the Pacific Decadal Oscillation (PDO), the principal mode of SST variability in The North Pacific. Notably, during negative phases of the PDO, when warm SST anomalies are present in the central and western Pacific, blocks tend to be relatively short-lived and zonal anomalies tend to be stronger than during positive phases of the PDO. Our analysis leads to the tentative conclusion that SST anomalies have a significant impact on the atmosphere in a manner dependent on the atmospheric basic state. This conclusion needs to be tested by extending the period of record from 10 to 40 years. (See: Bond, N.A., and D.E. Harrison (2000). The Pacific Decadal Oscillation, air-sea interaction and central north Pacific winter atmospheric regimes. Geophys. Res. Lett., 27(5), 731-734.)

In addition, the quality of the NCEP/NCAR Reanalysis surface forcing fields was evaluated for the Northeast Pacific and Bering Sea using a series of buoy measurements from 1995 through 2000. Emphasis was placed on surface winds and short wave radiation, as they are crucial parameters for forcing numerical ocean models. Comparisons with the Reanalysis for the Northeast Pacific indicate that it adequately represents the winds, but that it overestimates the downward short wave radiation by approximately 20 W/m2. (See: Ladd, C. and N.A. Bond, 2002: Evaluation of the NCEP-NCAR Reanalysis in the Northeast Pacific and the Bering Sea. J. Geophys. Res. In press.)

ERS-2 altimeter data for 27 October 1998



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SSH anomaly from the 1/4° global NLOM running in real-time at FNMOC that includes assimilation of TOPEX/Poseidon and ERS-2 altimeter data
27 October 1998

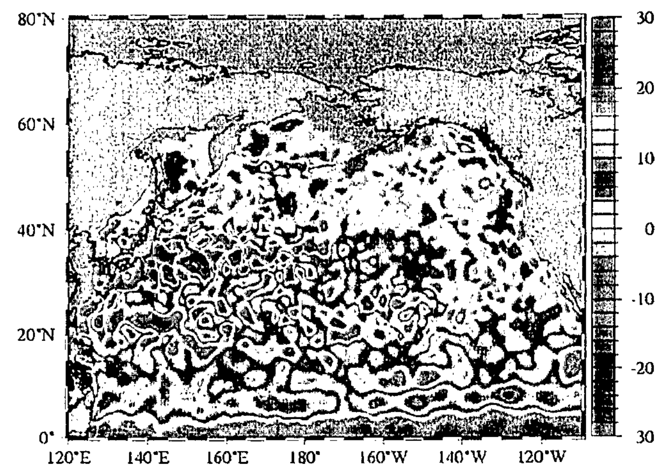

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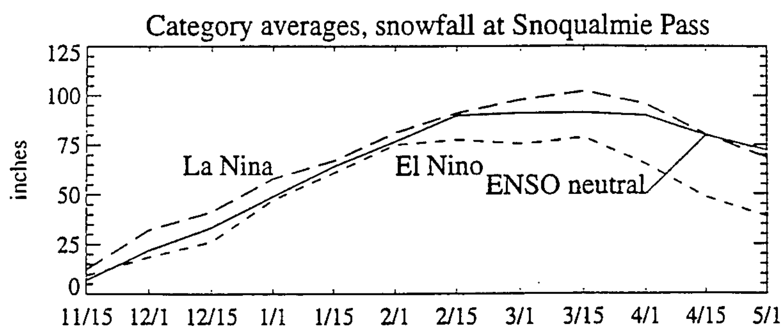
Figure 2 ERS-2 sea surface height 27 October 1988 (left) assimilated into Fleet Numerical Meteorology and Oceanography Center layered ocean model. (right).



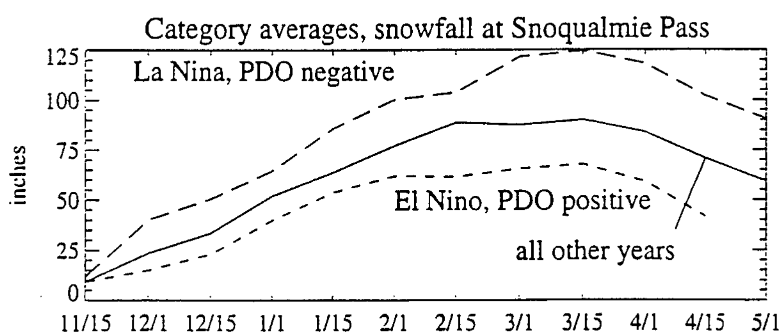


Figure 3 Effects of Pacific Decadel Oscillation positive and negative cycles on snowfall near Seattle.

An example of the effects during PDO positive and PDO negative years on snowfall near Seattle is given in Figure 3.

5) Summary of Research Cruises

Moana Wave Engineering Cruise, *R/V Moana Wave*, 7-9 April 1998. Honolulu – Honolulu, Chief Scientist: Hugh Milburn, NOAA-PMEL.

> This was an engineering cruise for deep-water tests of new Datasonics acoustic modems, inductively coupled data telemetry hardware and software, bottom instrument location software, and other systems that will be used on the real time tsunami warning system and the NOPP North Pacific moorings program.

Sproul98: Acoustic Modem Test Cruise. *R/V Robert Gordon Sproul*, 25–26 August 1998, San Diego, California – San Diego, California, Chief Scientist: Matthew Dzieciuch, SIO/UCSD.

> The was an engineering cruise to characterize the performance of the Datasonics acoustic modem link in a situation similar to that to be used in the NOPP deployment in September 1998.

NOPP98 Deployment Cruise, *NOAA Ship Ronald H. Brown*, 23 September – 3 October 1998, Victoria, British Columbia – Seattle, Washington, Chief Scientist: Hugh Milburn, NOAA-PMEL.

> The surface and subsurface moorings were deployed at OWS PAPA on this cruise.

NOPP98 Recovery Cruise, *R/V Wecoma*, 6–14 June 1999, Kodiak, Alaska – Seattle, Washington, Chief Scientist: Rick Miller, NOAA-PMEL.

> The moorings previously deployed at OWS PAPA were successfully recovered on this cruise.